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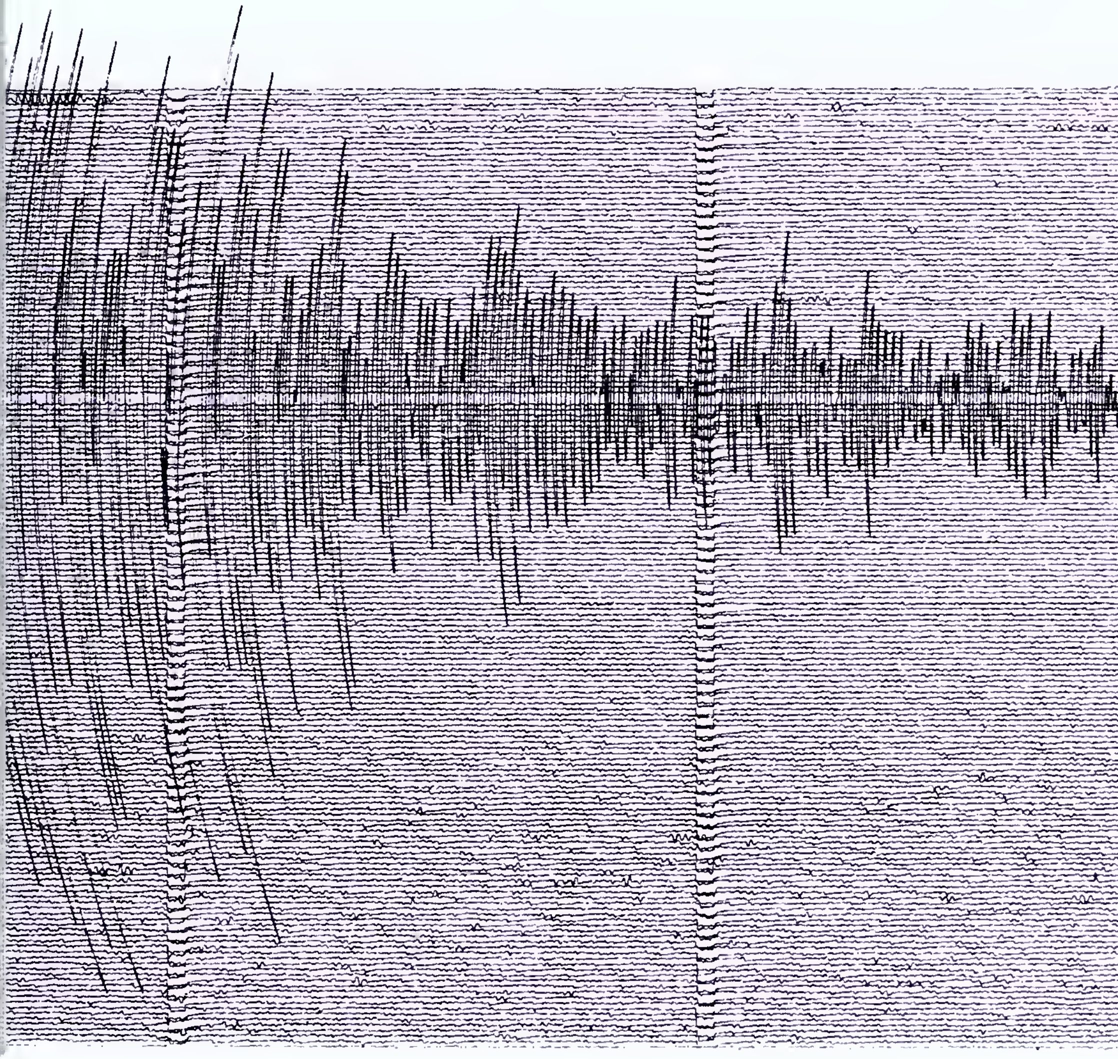

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ON THE COVER: An actual seismograph recording in Pennsylvania on September 6, 1988, of a Richter magnitude 4 earthquake that had an epicenter in Kentucky. Recorded on the seismograph at Millersville University, Millersville, Pennsylvania.

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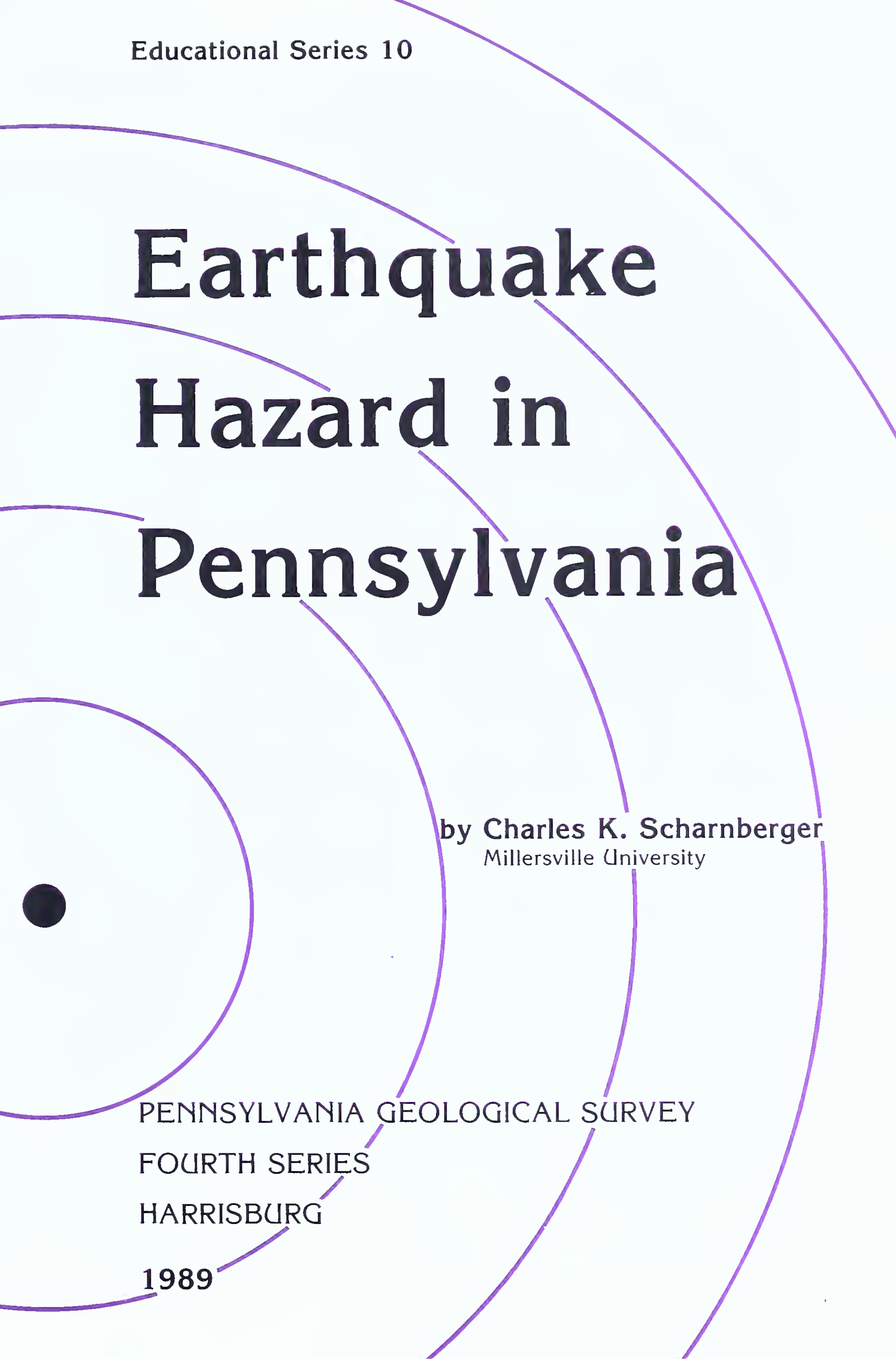

Earthquake Hazard in Pennsylvania

by **Charles K. Scharnberger**
Millersville University

PENNSYLVANIA GEOLOGICAL SURVEY
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Pennsylvania. Topographic
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Earthquake Hazard in Pennsylvania

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Charles K. Scharnberger

Introduction

Compared to other states, especially California and Alaska, Pennsylvania is relatively free of earthquake activity. Even considering only the eastern half of North America, Pennsylvania has experienced fewer and milder earthquakes than most other states or Canadian provinces. Nevertheless, earthquakes do occur in our Commonwealth, and Pennsylvania may be subject to the effects of earthquakes that have epicenters located outside our borders. Therefore, it is worth considering how much hazard earthquakes present to Pennsylvanians.

What is an Earthquake?

Earthquakes occur when there is a sudden release of stored energy from a portion of a fault plane within the earth. Faults are fractures in the lithosphere—the rather brittle outer layer of the solid earth. Energy in the form of *strain*, small elastic distortion of the lithosphere, accumulates over a period of time due to *stress* acting on the rock of the lithosphere. The origin of this stress is believed by most geophysicists to be slow convective motion, driven by heat energy, which occurs below the lithosphere in the mantle. One consequence of this slow convection is the fragmentation of the lithosphere into tectonic plates, and the slow movement of these plates relative to each other. Much of our understanding of earthquakes, as well as other geologic phenomena such as volcanic eruptions and mountain-building, is based on this theory of *plate tectonics.*

The rock of the lithosphere can accommodate only so much strain energy. Eventually, the rock must fracture. When this happens, strain is relieved, the stress level drops, some energy is converted into heat, some movement (slip) occurs along the plane of fracture (the fault plane), and some energy is radiated away from the area of fracture in the form of elastic waves—called *seismic waves*—which travel through the earth or along the surface of the earth. The arrival of these seismic waves at a point on the surface causes rapid and complex motions of the ground. This is what we feel as an earthquake. Once a fault has formed as the result of an initial fracture, earthquakes are likely to recur along the same fault, because this plane is now a zone of weakness in the lithosphere.

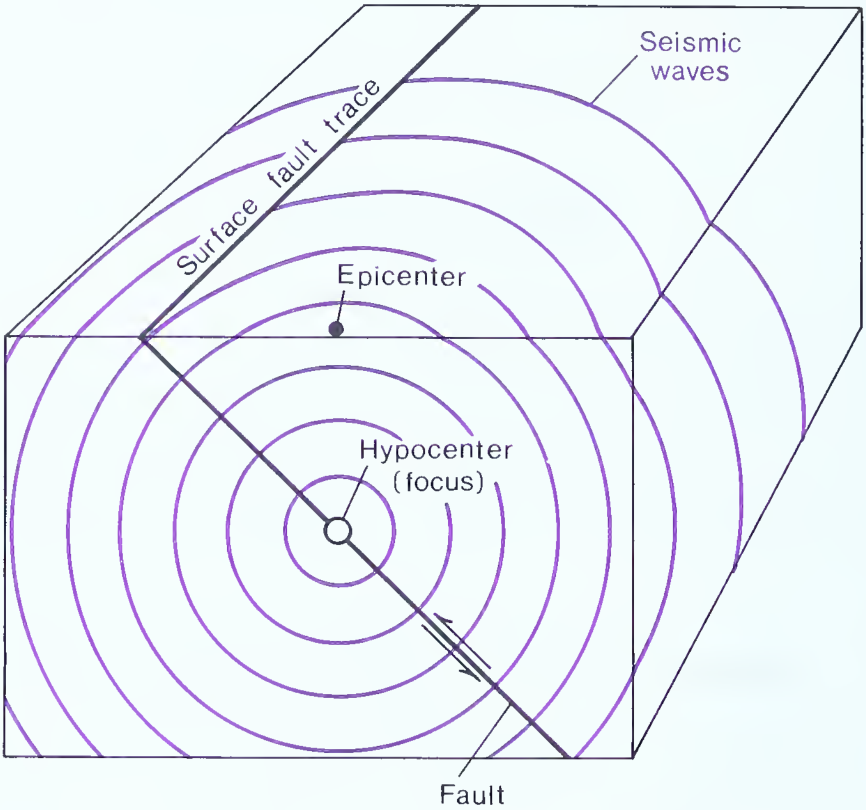

Figure 1. Relationship among fault plane, fault trace on surface of the earth, earthquake hypocenter (focus), epicenter, fault slip (arrows), and seismic waves. (Based on Plummer, C. C., and McGeary, David, *Physical geology*, 4th ed., Figure 16.2, p. 345. Copyright © 1988 by Wm. C. Brown Publishers, Dubuque, Iowa. All rights reserved.)

Figure 1 shows the relationship of a fault plane to the origin point of the seismic waves (called the *hypocenter* or *focus* of the earthquake) and the *epicenter*, the point on the surface of the earth directly above the hypocenter. Note that, unless the attitude of the fault plane is vertical, the epicenter will be located some distance from the trace of the fault along the surface of the earth. In eastern North America, no earthquake in historic time has caused a displacement of the surface along a fault trace.

Earthquakes and Plate Boundaries

The great majority of the earthquakes in the world occur along the boundaries between tectonic plates. The reason for this is not completely clear, but it may be that stress levels are higher along plate boundaries, or that strain energy builds up more rapidly in those areas. Pennsylvania today is far from the nearest plate boundary—the Mid-Atlantic Ridge, some 2,000 miles to the east. However, about 200 million years ago, when the Atlantic Ocean was just beginning to open as the supercontinent Pangaea broke up, the east coast of North America was at a plate boundary, and many faults in eastern North America were formed at that time. Measurements show that the maximum stress in this region now is a compression acting horizontally in approximately an east-west sense. Where 200-million-year-old faults are oriented roughly north-south, they are susceptible to reactivation by the present-day stress field. This seems to be what is happening to cause at least some of the earthquakes felt in eastern North America.

Earthquake Magnitude

Seismic waves are detected and measured by seismographs. The energies of earthquakes are compared on the basis of their magnitudes, a concept first defined in the 1930's by Charles Richter of the California Institute of Technology. Richter wished to have a single number to describe an earthquake, independent of the distance from the epicenter at which the earthquake waves were recorded. The system he devised commonly is called the *Richter Scale*, a term that often leads to the mistaken impression that there is a kind of physical instrument—a scale similar to those used to measure weights—to which the term applies. The numbers of the Richter Scale are logarithms; that is, numbers that express powers of 10. As originally defined by Richter on the basis of California earthquakes recorded locally on a particular type of seismograph, the magnitude represented the maximum amount of ground movement at a distance of 100 kilometers (62 miles) from the epicenter of an earthquake. Each whole number on the scale represented a 10-fold difference in this amplitude of ground motion.

As the concept of magnitude came to be used worldwide and had to be calculated from many different types of seismographs, new ways of defining the magnitude were introduced, so that today several different magnitude numbers might be found for the same earthquake. Thus, magnitudes are useful mostly for comparing earthquakes (the purpose Richter had in mind), rather than for finding the actual energy of an earthquake with more than rough precision.

There is no upper or lower limit to the Richter Scale, but as a matter of historical fact, no magnitude greater than about 9 has ever been calculated for an earthquake. Earthquakes in eastern North America seldom have magnitudes greater than 5.

Earthquake Intensity

Before the development of the Richter Scale, earthquakes were compared on the basis of *intensity*. Today, intensity values are an important supplement to the magnitudes because intensity is a semiquantitative expression of the effects caused by an earthquake. These may be effects on people, on man-made structures, or on natural features of the landscape. Intensities are determined after the earthquake on the basis of field observations made by trained personnel, or from survey forms filled out by persons who experienced the earthquake. The U.S. Geological Survey uses reports sent in by postmasters, and compiles intensity data by postal ZIP code.

Obviously, intensity is not a single number for a particular earthquake, but varies from place to place. Usually, the intensity is greatest in the immediate vicinity of the epicenter and decreases with increasing distance from the epicenter. However, many factors affect intensity; among them are topography, type and thickness of soil, direction from the epicenter relative to regional rock structure, and type of bedrock. The greatest intensities are often caused by landslides induced by the seismic waves rather than by the direct effects of the waves.

In the United States, intensities are expressed in terms of the *Modified Mercalli Scale*. This scale was first proposed in Italy by Giuseppi Mercalli early in this century, and was modified in 1931 by the American seismologists H. O. Wood and F. Neumann (for this reason, it is also called the Wood-Neumann Scale). Table 1 is an abridged version of the Modified Mercalli Scale; Roman numerals usually are used to avoid confusion with earthquake magnitude.

Earthquake Hazard and Earthquake Risk

Although the words "hazard" and "risk" may seem synonymous, there is a distinction to be made between them, at least for natural phenomena. Gere and Shah (1984, p. 112) define "hazards" as "those natural events that threaten life and property." "Risks" are defined as "everything that we have to lose—including both life and property." Thus, in two areas that have similar earthquake histories, the hazard may be approximately equal, but the risk is much greater in the area that is more densely populated. Hazard and risk together determine probability of loss, the factor most relevant to public policy questions. In this paper, only the question of seismic hazard in Pennsylvania is addressed, and no attempt is made to evaluate seismic risk.

Table 1. *The Modified Mercalli Scale of 1931 (Abridged Version)*

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on the upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on the upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration is like the passing of a truck. Duration is estimated.

IV. During the day felt indoors by many, outdoors by few. At night some are awakened. Dishes, windows, and doors are disturbed; walls make a creaking sound. Sensation is like a heavy truck striking a building. Standing motor cars are rocked noticeably.

V. Felt by nearly everyone; many are awakened. Some dishes, windows, etc., are broken; a few instances of cracked plaster occur; unstable objects are overturned. Disturbance of trees, poles, and other tall objects is sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many are frightened and run outdoors. Some heavy furniture is moved; a few instances of fallen plaster or damaged chimneys occur. Damage is slight.

VII. Everybody runs outdoors. Damage is *negligible* in buildings of good design and construction; *slight* to *moderate* in well-built ordinary structures; *considerable* in poorly built or badly designed structures. Some chimneys are broken. Noticed by persons driving motor cars.

VIII. Damage is *slight* in specially designed structures; *considerable* in ordinary substantial buildings, with partial collapse; *great* in poorly built structures. Panel walls are thrown out of frame structures. Chimneys, factory stacks, columns, walls, and monuments fall; heavy furniture is overturned. Sand and mud are ejected from the ground in small amounts. Changes occur in well water. Persons driving motor cars are disturbed.

IX. Damage is *considerable* in specially designed structures; well-designed frame structures are thrown out of plumb; damage is *great* in substantial buildings, with partial collapse. Buildings are shifted off their foundations. Ground is cracked conspicuously. Underground pipes are broken.

X. Some well-built wooden structures are destroyed; most masonry and frame structures are destroyed along with their foundations. Ground is badly cracked. Rails are bent. Considerable landslides occur on river banks and steep slopes. Sand and mud are shifted. Water is splashed (slopped) over banks.

XI. Few, if any, masonry structures remain standing. Bridges are destroyed. Broad fissures occur in the ground. Underground pipelines are completely out of service. Earth slumps and land slips occur in soft ground. Rails are bent greatly.

XII. Damage is total. Waves are seen on the ground surface. Lines of sight and level are distorted. Objects are thrown upward into the air.

Hazard of Earthquakes Having Epicenters Outside Pennsylvania

Historically, large earthquakes have occurred in three regions of eastern North America: (1) the Mississippi Valley, especially near the town of New Madrid, Missouri; (2) the St. Lawrence Valley, especially near the mouth of the St. Lawrence River, where a magnitude 6 earthquake occurred in November 1988; and (3) Charleston, South Carolina.

New Madrid, Missouri

Three great earthquakes struck the vicinity of New Madrid in December 1811, January 1812, and February 1812. Although there were no seismographs to record these events, each earthquake in the series is estimated to have had a magnitude in excess of 7. These earthquakes were felt in western Pennsylvania, but no damage is known to have occurred there (Abdypoor and Bischke, 1982; all other references to the effects of large historic earthquakes in Pennsylvania are from this source). It is unlikely that future New Madrid earthquakes would be any greater than those of 1811–12, so Pennsylvanians probably do not have to worry about a threat from that quarter.

The St. Lawrence Region

One of the largest earthquakes to have occurred in eastern North America since the time of historic records occurred in 1663 and had an epicenter in Quebec, probably not far from that of November 25, 1988. According to reports of French missionaries, the earthquake of February 5, 1663, triggered large rockslides along the banks of the St. Lawrence; the magnitude is estimated to have been about 7. An earthquake on February 28, 1925, in this area was recorded by seismographs, and its magnitude was calculated at 7.0. It was felt with intensity IV in northeastern Pennsylvania. The earthquake of September 4, 1944, although of relatively modest magnitude (5.6), caused serious damage to the towns of Cornwall, Ontario, and Messina, New York. Northwestern Pennsylvania falls within a western extension of the St. Lawrence seismic region; however, historic earthquakes in this part of the region have been less severe than those farther east. The only St. Lawrence earthquake known to have caused damage in Pennsylvania (at Sayre, Bradford County) occurred on August 12, 1929, and had an epicenter near Attica, New York.

Charleston, South Carolina

Charleston was the site of the largest historic earthquake to have occurred along the eastern seaboard. On August 31, 1886, an earthquake with estimated magnitude between 6 and 7 produced intensities as high as X in the vicinity of Charleston. The intensity was IV throughout most of southern and eastern Pennsylvania. Charleston is 600 miles from Philadelphia, so it seems that, as in the case of New Madrid, a recurrence of the great Charleston earthquake would pose little hazard to Pennsylvania.

Other East Coast Areas

Boston, Massachusetts, felt earthquake shocks in 1744, 1755, 1903, and 1925. The largest of these seems to have been the 1755 event, which had an epicenter offshore near Cape Ann. This earthquake was felt strongly in eastern Pennsylvania, and had an intensity around IV or V in Philadelphia. Northeastern Pennsylvania is, at its closest point, about 230 miles from Cape Ann. This is close enough that intensities of VI might be expected in Pennsylvania from a magnitude 7 earthquake.

Southeastern New York and northern New Jersey have been the sites of moderate earthquakes. Perhaps the largest of these was on December 18, 1737, felt with intensity VII in New York City and intensity IV in eastern Pennsylvania. It is impossible to estimate the probability of a magnitude 7 earthquake occurring in northern New Jersey. However, such an earthquake, if it did occur, would almost certainly produce intensities as high as VIII in eastern Pennsylvania.

Hazard of Earthquakes Having Epicenters in Pennsylvania

Seismicity in Pennsylvania

Figure 2 shows the locations of historic epicenters in Pennsylvania; a list of Pennsylvania earthquakes is given in Table 2. The seismic history of Pennsylvania has been poorly known until recently. Sometimes, nonseismic events such as mine collapses have been mistaken for earthquakes. Many historic earthquakes were forgotten until the work of

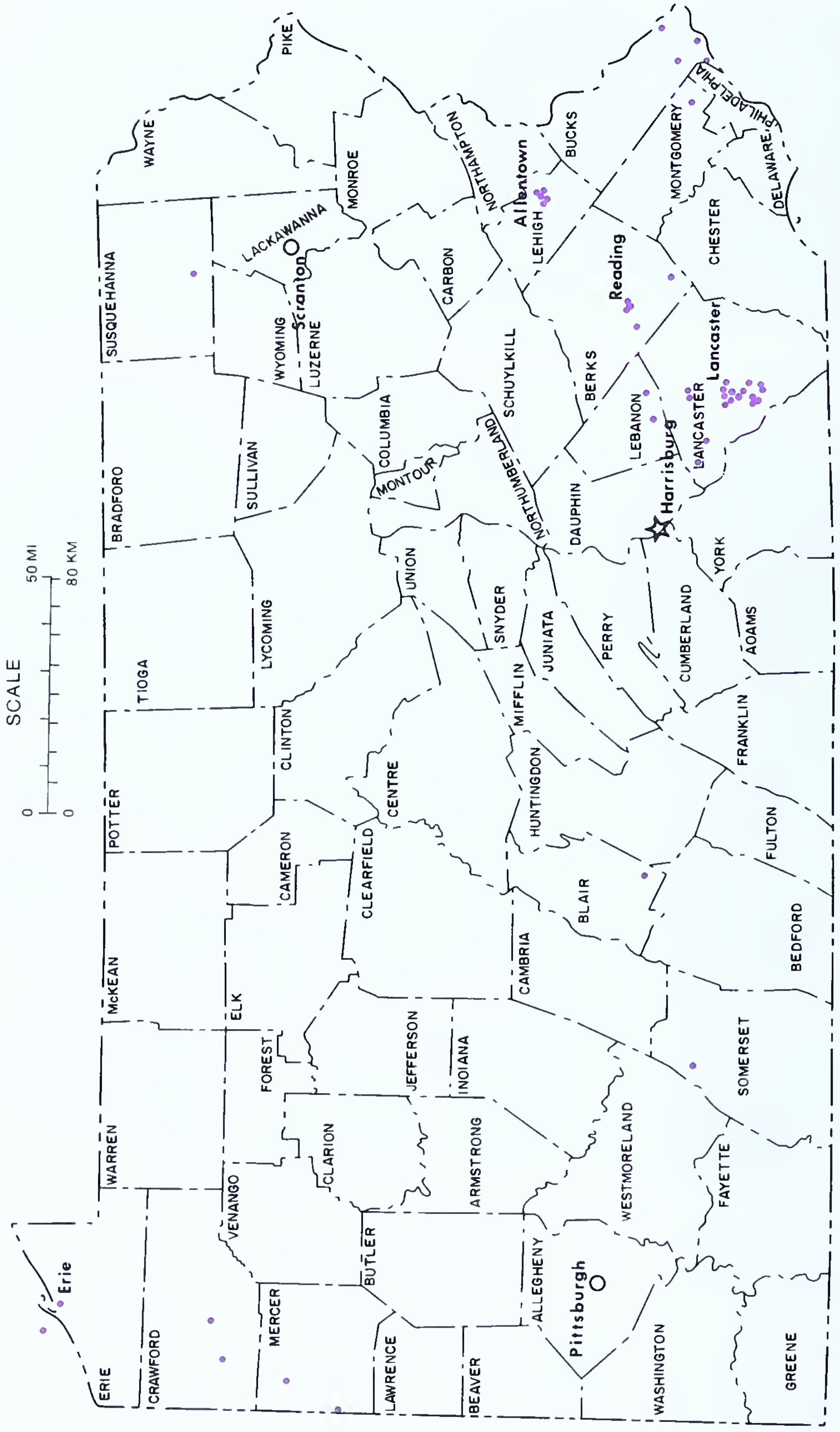

Figure 2. Locations of historic earthquake epicenters in Pennsylvania. Many locations are approximate.

Table 2. *Known Earthquake History of Pennsylvania Through January 1989*

Date (local time)	Location of epicenter	Magnitude[1]	Remarks
	LANCASTER SEISMIC ZONE		
1738 or 1739	(?)		
Dec. 17, 1752	(?)	3.6*	
Sept. 1793	(?)		
Jan. 11, 1798	Lancaster(?)		
Nov. 20, 1800	Lititz(?)	4.1*	
Jan. 27, 1801	Lancaster(?)		
Mar. 19, 1818	Lancaster(?)		
Aug. 21, 1820	Mt. Joy(?)	3.4*	
May 4, 1822	Lancaster(?)		
Sept. 5, 1829	Lancaster(?)		
Feb. 5, 1834	Marticville(?)	4.0*	
Sept. 17, 1865	Willow Street(?)		
Nov. 7, 1866	(?)		
Jan. 15, 1885	Schaefferstown		
Mar. 8, 1885	Lancaster(?)		
Sept. 26, 1886	Elizabethtown(?)		
Mar. 8, 1889	Conestoga(?)	4.3*	
May 12, 1964	Cornwall	3.2*	
Dec. 7, 1972	Lititz		
July 16, 1978	Conestoga	3.0	
Oct. 6, 1978	Lancaster	3.1	
Apr. 22, 1984	Marticville	4.1	Foreshock near Mt. Nebo 4 days earlier; many aftershocks
Sept. 19, 1984	Lancaster		
May 2, 1986	Conestoga	2.6	
	NORTHWESTERN PENNSYLVANIA		
Sept. 15, 1852	Meadville		
Aug. 17, 1873	Sharon		
Sept. 26, 1921	Erie		
Oct. 29, 1934	Erie		Aftershock near Albion 7 days later
Aug. 26, 1936	Greenville		
Apr. 14, 1985	Conneaut Lake	3.2	
	LEHIGH COUNTY		
May 31, 1884	Allentown		
May 31, 1908	Allentown		

Table 2. *(Continued)*

Date (local time)	Location of epicenter	Magnitude[1]	Remarks
LEHIGH COUNTY *(Continued)*			
June 22, 1928	Allentown		
Nov. 23, 1951	Allentown		
Sept. 14, 1961	Allentown		
BERKS COUNTY			
May 28, 1906	Geigertown		
June 8, 1937	Reading		
Jan. 7, 1954	Sinking Spring		Beginning of earthquake swarm lasting 1 year
June 25, 1972	Wyomissing		Beginning of earthquake swarm lasting a few days
Aug. 12, 1973	Wyomissing		
PHILADELPHIA AREA			
Dec. 27, 1961	Bristol		
Mar. 5, 1980	Abington		Foreshock 3 days earlier; aftershock 6 days later
Nov. 14, 1981	Lower Bucks Co.		
Apr. 12, 1982	Cornwells Heights		
May 12, 1982	Lower Bucks Co.		
BLAIR COUNTY			
July 15, 1938	Clover Creek		
SOMERSET COUNTY			
Feb. 3, 1982	Jennerstown	2.6	
SUSQUEHANNA COUNTY			
Aug. 14, 1982	Hop Bottom	2.1	

[1] Asterisk indicates inferred magnitude.

Armbruster and Seeber (1987) brought them to light. The most active part of the state is the Lancaster seismic zone of Lancaster and Lebanon Counties. Next most active is northwestern Pennsylvania, from Erie southward along the Ohio border. Earthquakes are also known from Lehigh, Berks, Montgomery, Bucks, Blair, Somerset, and Susquehanna Counties. Because of the number and magnitude of the earthquakes in the Lancaster seismic zone, that area is examined here in some detail.

Magnitude-Frequency Relationship for the Lancaster Seismic Zone

Gutenberg and Richter (1954) discovered a simple relationship between the magnitudes of earthquakes and the frequency of their occurrence. When one plots on a logarithmic scale the number of earthquakes that have magnitudes equal to or greater than a given value against the magnitude numbers, the points fall on a straight line having negative slope. From the slope of this line, one might predict the number of earthquakes expected to occur within the period of time for which the plot has been made, up to any magnitude cutoff. The result of doing this for earthquakes of the Lancaster seismic zone is shown in Figure 3. In making this plot, the earthquake of September 17, 1865, has been considered as an event having a magnitude of at least 4, based on contemporary newspaper accounts, and the foreshock of the April 22, 1984, earthquake has been included in the count of events having magnitudes of 3 or greater. The magnitudes of many of the early earthquakes in

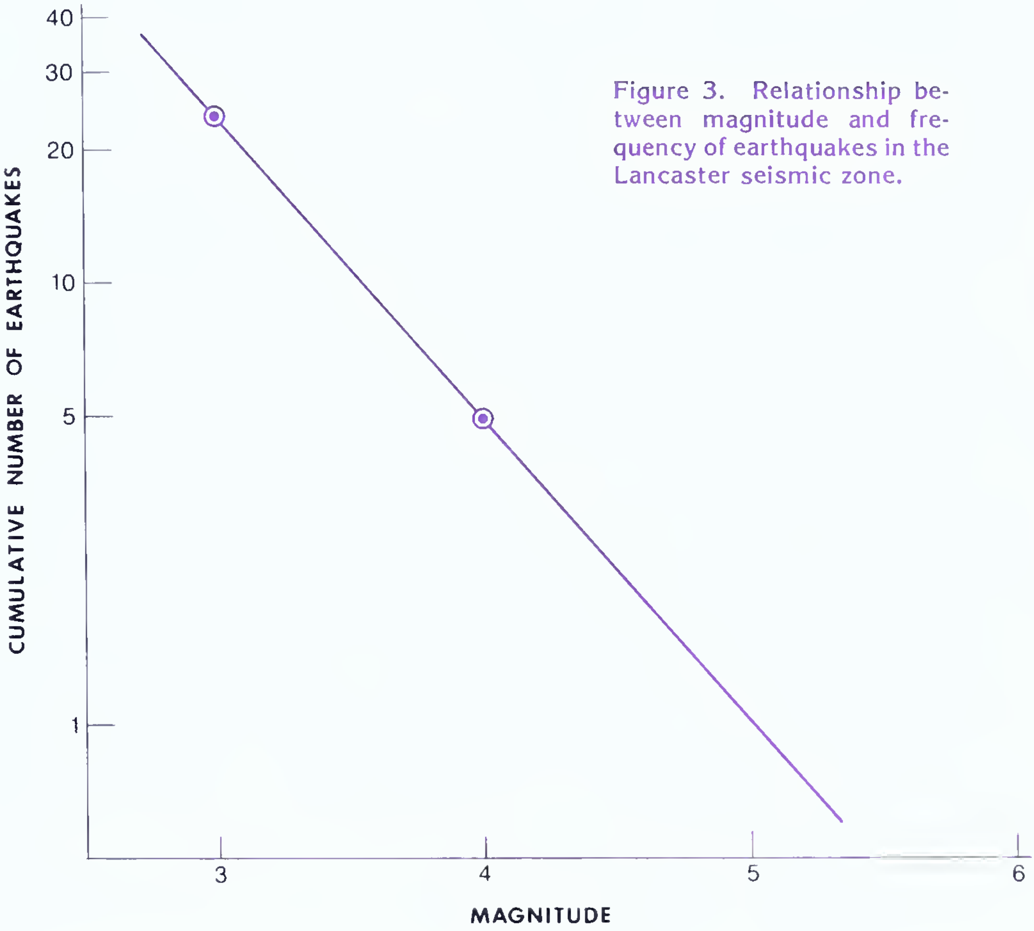

Figure 3. Relationship between magnitude and frequency of earthquakes in the Lancaster seismic zone.

the historic record are not known very precisely, the historical record may not be complete, and the total number of earthquakes is small; therefore, Figure 3 must be interpreted with some caution.

The slope of the line in Figure 3 is −1.13. Extending this line to magnitude 5, we see that one such event is expected to occur in about 250 years, the length of the historic record. No earthquake of this great a magnitude is known to have occurred in the Lancaster seismic zone, but a count of 0 when the expected count is only 1 does not have a great deal of significance. Based on this analysis, then, it seems possible that an earthquake having a magnitude of around 5 could occur in the Lancaster area.

A Probabilistic Approach

Another way to try to estimate the seismic hazard in the Lancaster seismic zone is to use the probabilistic method applied by Howell (1979) to all of Pennsylvania. Howell's analysis suffered from the fact that much of the historic earthquake record was not known in 1979, and from the inclusion of a number of nonseismic events, particularly the 1954 Wilkes-Barre mine collapse. His method, however, seems worth trying on what probably is a fairly complete record for the Lancaster seismic zone.

Howell's approach was based on the same method used to estimate the likelihood of extreme floods, such as the so-called 100-year or 200-year flood. The essence of the method is to divide the historical record into time intervals of equal length and then to identify the largest earthquake to have occurred in each interval. The usual interval is one year, but because earthquakes are rather rare events, it seems better to use a longer time interval; for the present study, four-year periods were used, beginning in 1730. There are 62 four-year periods in the 258 years from 1730 through 1987. The earthquakes are plotted on probability paper (Figure 4) in order of increasing magnitude and increasing improbability. The improbability of an event is $(1-P)$, where P is the probability. The smallest magnitude used was 2.6; the smaller historical earthquakes for which no magnitude is known were assigned an estimated magnitude of 3.0. Magnitudes for the larger historical events have been taken from Armbruster and Seeber (1987).

As an example, consider the earthquake of 1820, which had an estimated magnitude of 3.4 (Table 2). There are 17 time periods in which earthquakes have occurred. In seven of these, the magnitude of the largest earthquake was greater than or equal to 3.4. From this, we can conclude that the improbability of an earthquake having a magnitude of 3.4 or greater occurring in any four-year period is $(62-7)/62 = 0.89$. This corresponds to a probability of 0.11 (or 11 percent) that such an

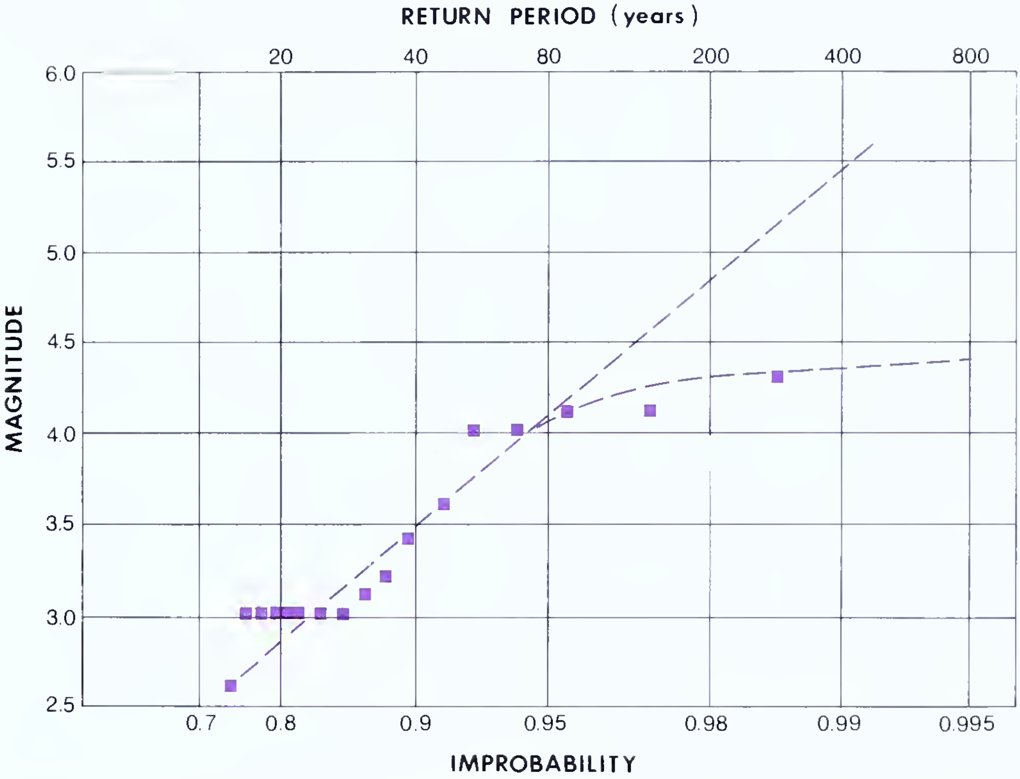

Figure 4. Relationship among magnitude, improbability, and the return period of earthquakes in the Lancaster seismic zone.

earthquake *will* occur. This is approximately 1 chance in 10, and since there are 40 years in 10 four-year periods, we could refer to a magnitude 3.4 event as the "40-year earthquake" for the Lancaster seismic zone. Note, however, that this does not mean that an earthquake of at least that magnitude is certain to occur every 40 years. The probability of the "40-year earthquake" actually occurring in a 40-year period is $(1 - 0.9^{10}) = 0.65$, or 65 percent.

If there is no upper bound to the magnitudes that can occur, then the distribution on probability paper should be a straight line. A fairly good straight-line fit can be made through the first 15 points on Figure 4. The extension of this line suggests that the 200-year earthquake has a magnitude of about 4.8 and the 400-year earthquake has a magnitude of about 5.5 (a 1 percent chance of a magnitude 5.5 earthquake occurring in any 4-year period). The return period for a magnitude 5.0 earthquake is about 250 years, a result consistent with the result obtained from the first method of analysis.

However, considering the remaining two points in Figure 4, we see that the curve through all 17 points deviates significantly from a straight line. This suggests that the magnitudes of earthquakes in the Lancaster seismic zone are not unbounded, but rather have a limit of about 4.5.

Conclusion

Two of the areas that have generated the largest historical earthquakes in eastern North America—New Madrid, Missouri, and Charleston, South Carolina—are too far away for earthquakes having epicenters there to cause damage in Pennsylvania, although earthquakes occurring in those areas that have magnitudes near 7 would be felt in Pennsylvania. Eastern Massachusetts is closer, and a magnitude 7 earthquake there could produce intensity VI effects in northeastern Pennsylvania. Similar intensities might be expected in north-central and northwestern Pennsylvania from earthquakes that have epicenters in the western part of the St. Lawrence zone. The possibility that a magnitude 7 earthquake could occur having an epicenter near New York City cannot be completely discounted, and such an earthquake could produce significant damage (intensity VIII) in eastern Pennsylvania.

Within Pennsylvania, Lancaster, York, Erie, Reading, Allentown, and Philadelphia probably will continue to feel earthquakes generated on local faults. A few earthquakes are likely to occur in other areas, including, perhaps, some that up to now have not been known to be seismic. The largest Pennsylvania earthquakes have been generated in the Lancaster seismic zone, and analysis of the historic record suggests a limit of about 4.5 on the magnitudes of earthquakes that are likely to occur there. This conclusion, however, must be regarded as a very tentative one.

The earth is an extremely complex natural system; even after 200 years of organized geological study, we understand only partly how our planet works. This is true for seismology as much as for any branch of the earth sciences, and the earth may have some seismic surprises in store for us. Thus, the best we can say is this: based on the historic record of earthquakes in eastern North America and on the current state of scientific knowledge, earthquakes pose only a slight hazard in Pennsylvania.

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